# Results Of A Field Study Of Underfloor Air Distribution

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## ABSTRACT

Underfloor air distribution (UFAD) is a method of supplying conditioned air via floor mounted air supply diffusers. We measured several aspects of the performance of an UFAD system in an office building. The air change effectiveness was very close to unity, which is comparable to that measured in buildings with typical overhead air distribution. The pollutant removal efficiency for carbon dioxide was 13% higher than expected with well-mixed air. The increase in air temperatures with height above the floor was only 1 to 2 $^{o}$C. This amount of thermal stratification could reduce the sensible energy requirements for cooling of outdoor air by approximately 10%. The occupant's satisfaction with thermal conditions was well above average. Thus, the results of this study provide some evidence of moderate energy and IAQ-related benefits of UFAD; however, the benefits need to be confirmed in other studies.



## INDEX TERMS

air distribution, thermal stratification, measurements, underfloor, ventilation efficiency,


## INTRODUCTION

Underfloor air distribution (UFAD) systems supply a mixture of recirculated and outdoor air to occupied spaces from air supply registers located in raised floors. For a number of reasons, the use of UFAD is increasing rapidly in the US. UFAD supply diffusers are easy to relocate and the underfloor air supply plenum eases the routing of wiring. Because UFAD systems supply higher temperature air than conventional heating, ventilating, and air conditioning (HVAC) systems, UFAD can increase the opportunity to use outdoor air for free cooling and also increase the coefficient of performance of air conditioning. Based primarily on laboratory studies, UFAD can cause a vertical air temperature gradient that can decrease the energy required for air conditioning. An upward displacement airflow pattern leading to an improvement in ventilation efficiency is another widely reported advantage of UFAD. The air change effectiveness (ACE) is an index commonly used to quantify ventilation efficiency (ASHRAE 2002). In practical terms, the ACE indicates the effective ventilation rate at the breathing zone divided by the ventilation rate that would occur through the indoor space with the same amount of outdoor air supply and perfect mixing of the indoor air. If the ACE is greater than unity, either IAQ at the breathing zone is normally improved or the minimum required rate of outdoor air supply could be reduced (multiplied by 1/ACE) to save energy. No prior publications documenting measurements of ACE in an actual building with UFAD were identified. Therefore, a primary objective of this study was to determine whether UFAD in the study building resulted in an ACE above unity. Secondary objectives were to add to the limited information on the thermal stratification, occupant satisfaction with thermal conditions, and occupant satisfaction with air quality in buildings with UFAD.

## STUDY METHODS

The measurements were performed in a two-storey, energy-efficient, 3,100 m$^2$ U.S. office building with a ceiling height of 2.5 to 6.1 m. The conditioned air used to heat, cool and ventilate the building entered the occupied spaces through swirl-type air supply diffusers in the suspended floor. Air exited the occupied spaces through return grilles located 2.7 to 3.0 m above the floor. The flow rates of outdoor and recirculated air were constant and the heating and cooling of the supply air cycled on and off.

The ACE was determined from measured values of age of air. The reciprocal of an age of air can be informally considered a local ventilation rate. We used the tracer gas step-up procedure with sulfur hexafluoride ($SF_6$) tracer gas injected into the incoming outdoor airstreams. $SF_6$ concentrations were measured with infrared analyzers in exhaust airstreams, at return grilles, and at breathing-level (*BL*) locations. After $SF_6$ concentrations stabilized, ages of air were calculated using the equation

$$A_i = \int_0^{\infty}\left(1 - \frac{C_i(t)}{C_{\infty}(t)}\right)dt \tag{1}$$

where $A_i$ is the age of air at location *i*, *C* is the tracer gas concentration, *t* is the time elapsed since the start of tracer gas injection, and $C_\infty$ is the steady state tracer gas concentration. The ACE was calculated from the equation

$$\mathrm{ACE} = \tau_n / A_{avg} \tag{2}$$

where $\tau_n$ is the nominal time constant and $A_{avg}$ is the average age of air measured at the *BL* locations. The nominal time constant is the average age of air exhausted from the building and equals the age of air that would occur throughout the building with perfect mixing. Because we were most interested in the ACE where people spend most time, we also calculated local values of ACE, substituting the age of air at a return air grille for $\tau_n$, and replacing $A_{avg}$ with the age of air at a nearby seated or standing BL location. Our prior laboratory research indicated that the uncertainty in our measured values of ACE was approximately ±0.02 (Fisk et al. 1997). In field studies we anticipate more uncertainty. The ACE measurement standard (ASHRAE 2002) estimates a maximum uncertainty of ±0.16.

The local pollutant removal efficiency (*PRE*) is another indicator of ventilation efficiency, but the *PRE* indicates the efficiency of ventilation in controlling exposures to a real pollutant, which may have localized sources and be emitted with momentum. Thus, values of *PRE* can differ from values of ACE. We measured the *PRE* for $CO_2$, which should be representative of the *PRE* for other occupant-generated pollutants. The local *PRE* for $CO_2$ was calculated from

$$PRE = \Delta\overline{C_{RG}} \Big/ \Delta\overline{C_{bz}} \tag{3}$$

where $\Delta\overline{C}$ equals the time-average difference between an indoor and outdoor work-day concentration of $CO_2$, subscript "*RG*" refers to an indoor measurement at the return grille located nearest to the indoor measurement location, and subscript "*bz*" refers to an indoor measurement at a breathing zone height- 1.1 and 1.7 m, for seated and standing workers, respectively. The reported values of *PRE* are 9 to 12-hour averages from periods of occupancy. $CO_2$ concentrations were measured using infrared $CO_2$ analyzers calibrated at ten concentrations. The errors in our reported values of PRE were greatly reduced by using the same instrument to measure $CO_2$ at the return grill and breathing zone locations, the same instrument to measure all outdoor $CO_2$ concentrations, and by averaging approximately 200 values of PRE measured at the same location each workday. From propagation of error analyses, we estimated that uncertainty in the average of 200 values of *PRE* was 1.4%.

To quantify the thermal stratification, air temperatures were measured and logged at seven heights above the floor near the six sites of tracer gas and $CO_2$ monitoring. We also measured temperatures in the supply air plenums beneath the suspended floors. Because we were interested in the extent of stratification, small differences in sensor calibration were important, therefore, we applied a correction factor to each sensor based on data from a sensor intercomparison. After applying the correction factor, the estimated uncertainty in a calculated temperature difference was approximately ±0.1 $^{o}$C.

As detailed in Fisk et al. (2004), the amount of energy needed for sensible cooling of incoming outdoor air can be reduced by temperature stratification because the stratification enables a small increase in supply air temperature and corresponding increase in return air temperature. The amount of energy savings is proportional to the temperature difference $\Delta T$ between the air temperature in the occupied zone $T_{OZ}$ and the return air temperature $T_R$. For our analyses, the value of $T_{oz}$ was based on the average of all temperature data collected between the heights of 0.1 and 1.7 m . We calculated time-average values of $\Delta T$. To quantify the potential energy savings from thermal stratification we used the following equation

$$SF_{OA} = \frac{MX\Delta T}{MX(T_{OA} - T_R)} \qquad (4)$$

where M equals the product of mass flow rate and specific heat of air flowing through the cooling coil; X is the fraction of outdoor air in the supply airstream, and $T_{OA}$ is the outdoor air temperature. The savings fraction for outdoor air ($SF_{OA}$) represents the reduction in sensible heat removal required to cool outdoor air with thermal stratification divided by the sensible heat removal necessary to cool incoming outdoor air to the return air temperature.

Occupants were asked to complete a survey (Huizenga et al. 2003) accessed via the Internet that collected background information and asked occupants to rate their level of satisfaction with thermal comfort, air quality, and other factors. Respondents indicated satisfaction with a building condition on a seven-point scale, ranging from +3 representing very satisfied to –3 representing very dissatisfied, with zero indicating a neutral response. The survey also asked about satisfaction with the UFAD system. The responses from occupants in this study building were compared to average responses obtained from use of the survey in 67 buildings.

Measurements were performed in April of 2004. On study days, the maximum outdoor air temperature was 3 to 12 $^{o}$C and the minimum outdoor temperature was -1 to 2 $^{o}$C. Except early in the workday, the occupied spaces were normally being cooled.

**RESULTS**

The measured values of ACE based on the average exhaust airstream age of air and the average of ages of air at the seated breathing level (BL) ranged from 0.90 to 1.03 and averaged 0.98. When instead we used the average ages of air at the BL height of standing adults, the ACE ranged from 0.89 to 1.01 and averaged 0.96. The 16 measured values of <u>local</u> ACE based on ages of air at return grilles and at the BL height of seated workers ranged from 0.98 to 1.15 and averaged 1.04. The 16 <u>local</u> ACE values based on ages of air at return grilles and at the BL height of standing workers ranged from 0.98 to 1.10 and averaged 1.02. These ACE and local ACE values are not significantly different from unity given our estimated measurement uncertainty. Thus, the ACE in this building was indistinguishable from the ACE that would occur with perfectly mixed indoor air.

Figure 1 illustrates the results of PRE measurements. The 16 values of PRE based on $CO_2$ measurements at the seated BL height and at the nearby return grille ranged from 1.03 to 1.32

and averaged 1.13. Considering our estimated measurement uncertainty of 1.4%, the data indicate that the PRE for $CO_2$ at the seated BL height is significantly higher than in a space with well-mixed air, where PRE would equal 1.0. The 16 PRE measurements based on at the standing BL height ranged from 0.92 to 1.24 and averaged 1.05. The elevation above unity of 0.05 only slightly exceeds our uncertainty estimate. Because most workers are seated, the PRE value of 1.13 is most relevant. One can estimate that concentrations of other occupant-generated pollutants at BL are reduced by approximately 13% relative to an air distribution system that supplies the same amount of outdoor air and results in thorough mixing in rooms.

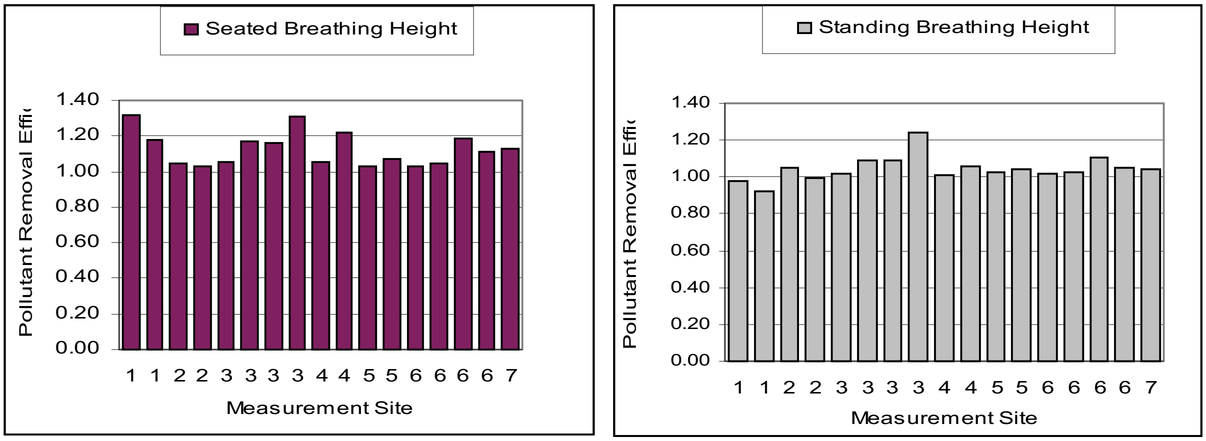
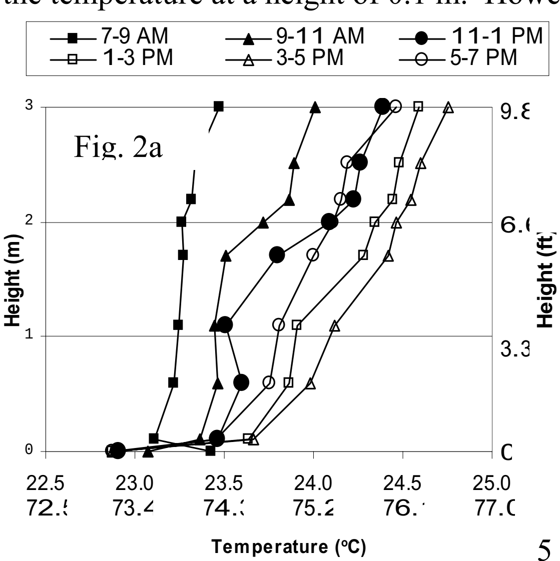



Figure 1. Measured values of pollutant removal efficiency (PRE) for carbon dioxide.

Figure 2a provides a typical example of the vertical profile of air temperature, based on two-hour average temperatures. The temperatures at a height of 0 m represent the temperatures of the supply air. At this measurement site, between 7 and 9 am the space was being heated, thereafter it was being cooled. Temperatures increased 1 $^{o}$C or less between heights of 0.1 and 3 m. Figure 2b provides an example of the air temperature profile at a first floor cubicle location where temperatures increased by the largest amount with height. At this location, the air temperature increased approximately 2 $^{o}$C between heights of 0.1 and 3 m (0.3 and 9.8 ft).

Table 2 indicates the degree of indoor temperature stratification and the heat removal effectiveness at each measurement site during periods of space cooling. The numbers in the table are time averages for all days of measurements. In absolute terms, the temperature stratification was small, i.e., the air temperature at the return grille was less than 1 $^{o}$C higher than the temperature at a height of 0.1 m. However, during these measurements the



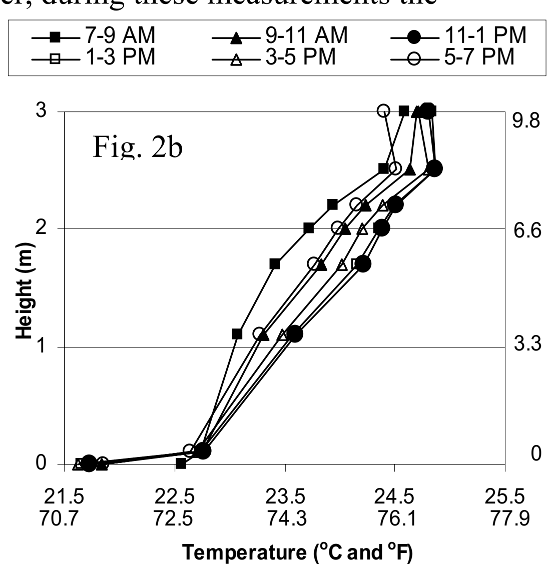



Figure 2. Examples of vertical temperature profiles.

temperature difference between the supply air and nearby return air grille averaged only 0.7 to 2.9 °C; thus, given the supply flow rates and internal heat generation, it was not possible to have a large temperature stratification in the occupied space. The difference between return air temperature and average temperature in the occupied zone ranged from 0.5 to 1.2 °C.

Table 2. Vertical temperature stratification (°C) during periods of cooling

| Site # | Space Type* | *T* at *RG* minus *T* Supply Air | *T* at *RG* minus *T* at 0.1 m | *T* at 1.7 m minus *T* at 0.1 m | *T* at 1.1 m minus *T* at 0.1 m | *T* at *RG* minus average *T* in occupied zone |
|---|---|---|---|---|---|---|
| 1 | *CS* | 2.9 | 1.9 | 1.3 | 0.7 | 1.2 |
| 2 | *PO* | 0.7 | 0.7 | 0.3 | 0.2 | 0.5 |
| 3 | *CS* | 1.6 | 0.9 | 0.4 | 0.2 | 0.7 |
| 4 | *CS* | 1.7 | 1.1 | 0.7 | 0.4 | 0.7 |
| 5 | *PO* | 0.7 | 0.7 | 0.3 | 0.3 | 0.5 |
| 6 | *CS* | 0.9 | 0.7 | 0.4 | 0.3 | 0.5 |

*T* = temperature *RG*= return grille *CS*= cubicle space *PO*= private office

The survey was available to 95 workers and 47% completed the survey. The response rate may have been diminished because many employees spent much work time away from the building. Compared to ratings in the 67 reference buildings, the average thermal comfort rating in the study building was well above average, at the 85$^{th}$ percentile and the average air quality rating was slightly below average, at the 40$^{th}$ percentile. However, many factors unrelated to the type of air distribution may have influenced these ratings. Fifty seven percent of respondents preferred the UFAD system to conventional overhead air distribution.

**DISCUSSION**

The measured values of ACE were very close to unity. In the U.S., the ACE is also normally close to unity with traditional overhead air distribution, thus, this study identified no significant improvement in ACE with UFAD. However, to the best of our knowledge, this was the first field study of ACE in a building with UFAD. With different UFAD equipment or operating conditions, such as less air recirculation, UFAD may result in a higher ACE. A related parameter, the PRE for $CO_2$ was about 13% higher than expected with thoroughly mixed indoor air. These results suggest that the UFAD process reduced exposures to occupant-generated pollutants by roughly 13%. However, we have no reference PRE data from buildings with typical overhead air distribution systems.

Although the absolute temperature stratification was small, the results indicate a potential for energy savings during air conditioning. To estimate the potential energy savings, we applied equation 4 and typical temperatures during air conditioning ($T_{OA}$ = 33 °C, $T_R$ = 25 °C). With these assumptions, each 1 °C difference between $T_R$ and $T_{OZ}$ corresponds to a 11% reduction in the energy for the sensible cooling of incoming outdoor air.

The high satisfaction with thermal comfort in the study building compared to satisfaction in reference buildings could possibly be due, in all or part, to the use of a UFAD system. However, the percentile ranks of thermal comfort ratings from four UFAD buildings that have completed the survey have varied considerably (95%, 36%, 85%, 48%), with a mean of 66%.

Therefore, in this very small sample, the level of thermal comfort in UFAD buildings was only moderately superior to the average level of thermal comfort in conventional buildings.

The major limitations of this study were that it examined the performance of a single building with UFAD and that HVAC operating conditions could not be modified. Thus, we caution against drawing general conclusions about UFAD based on this study.

## CONCLUSIONS

- The study did not identify an opportunity to save energy by reducing the rate of outdoor air supply because of a high value of air change effectiveness.
- The pollutant removal efficiency measured for carbon dioxide suggests a 13% reduction in exposures to occupant generated pollutants.
- The increase in air temperature from locations just above the floor to return grilles was 1 to 2 $^{o}$C. This amount of thermal stratification could reduce the sensible energy requirements for cooling of outdoor air by approximately 11% to 22%.
- The occupants' level of satisfaction with thermal conditions was well above average. This high satisfaction rating could possibly be due, in all or part, to the use of a UFAD system.

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